Nuclear Inst. and Methods in Physics Research, A 1046 (2023) 167807

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

Gain measurements of the first proof-of-concept PicoAD prototype with a ^{55}Fe X-ray radioactive source

M. Milanesio [a,*], G. Iacobucci [a], L. Paolozzi [a,b], M. Munker [a], R. Cardella [a], Y. Gurimskaya [b], F. Martinelli [a], A. Picardi [a], H. Rücker [c], A. Trusch [c], P. Valerio [a], F. Cadoux [a], R. Cardarelli [a], S. Debieux [a], Y. Favre [a], D. Ferrere [a], S. Gonzalez-Sevilla [a], R. Kotitsa [a,b], C. Magliocca [a], T. Moretti [a], M. Nessi [a,b], J. Saidi [a], M. Vicente Barreto Pinto [a], S. Zambito [a]

[a] Departement de Physique Nucleaire et Corpuscolaire (DPNC), University of Geneva, 24 Quai Ernest-Ansermet, CH-1211, Geneva 4, Switzerland
[b] CERN, CH-1211, Geneva 23, Switzerland
[c] Leibniz-Institut fur Innovative Mikroelektronik, Im Technologiepark 25, 15236, Frankfurt (Oder), Germany

ARTICLE INFO

Keywords:
Silicon sensors
Monolithic sensors
4D-tracking
Picosecond timing resolution
Gain layer

ABSTRACT

The Picosecond Avalanche Detector is a multi-junction silicon pixel detector devised to enable charged-particle tracking with high spatial resolution and picosecond time-stamping capability. A proof-of-concept prototype of the PicoAD sensor has been produced by IHP microelectronics. Measurements with a ^{55}Fe X-ray radioactive source show that the prototype is functional with an avalanche gain up to a maximum electron gain of 23.

1. Introduction

The MONOLITH H2020 ERC Advanced project aims at producing a monolithic silicon pixel ASIC with picosecond-level time stamping by using fast SiGe BiCMOS electronics and a novel sensor concept, the Picosecond Avalanche Detector (PicoAD) [1]. The fast SiGe BiCMOS electronics has been fully characterized in a prototype without gain layer [2].

The PicoAD uses a multi-PN junction to produce a continuous gain layer deep in the sensor volume. Fig. 1 shows a schematic layout of the PicoAD detector not to scale.

The figure shows, starting from the top:

- the pixels implantation, with large collection electrodes including the CMOS electronics;
- a 10 μm-thick high resistivity p-type epitaxial layer between the gain layer and the backside, in the following referred to as the drift region;
- a thin p^+-n^+ junction, i.e. the continuous gain layer. Four implant doses were used to form the gain layer, with dose one being the lowest and dose four the highest. The doses are equally spaced in the doping dose;
- a 5 μm-thick high resistivity p-type epitaxial layer between the gain layer and the backside, in the following referred to as the absorption region;
- the low resistivity p^+ backside substrate.

The thickness of the layers is not yet optimized for timing purposes.

The chip matrix of the proof-of-concept prototype has a total of 144 pixels (12 rows × 12 columns). Of them, four are connected to an analog front end, with a Hetero Bipolar Transistor (HBT) preamplifier, and two stages of HBT emitter followers to 500 Ω resistance on pad. These analog pixels are meant to characterize the sensor and the HBT preamplifier. The response in the gain of the analog pixels has been studied using a ^{55}Fe X-ray source.

2. Method

The measurements with ^{55}Fe X-ray source were performed in a clean room at the University of Geneva. A climate chamber has been used, varying the temperature between −20 °C and +20 °C. The outputs of the four analog pixels were sent to an oscilloscope with 1 GHz analog bandwidth and the waveforms were acquired for off-line analysis.

The ^{55}Fe X-ray source emits 5.9 keV photons. They mainly interact via a photoelectric effect in the silicon, producing a charge cluster inside the sensor that can be approximated as a point-like charge deposition of $n_i = 1640$ initial electrons. If the cluster is generated inside the absorption region, the electrons drifting towards the collection electrode produce avalanche gain. If the cluster is generated inside the drift region, the holes drifting towards the substrate produce avalanche

---

[*] Corresponding author.
E-mail address: Matteo.Milanesio@unige.ch (M. Milanesio).

https://doi.org/10.1016/j.nima.2022.167807
Received 29 July 2022; Received in revised form 5 October 2022; Accepted 7 November 2022

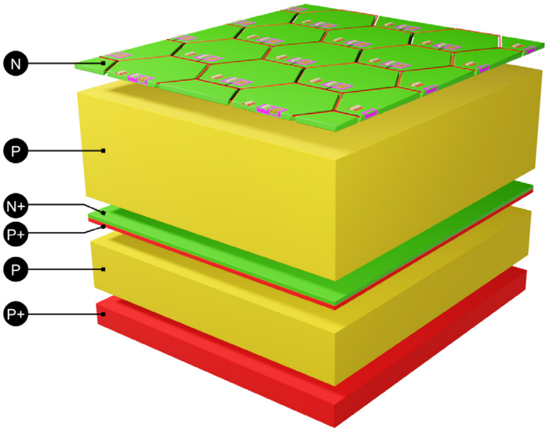

Fig. 1. Schematic layout of the PicoAD detector not to scale.

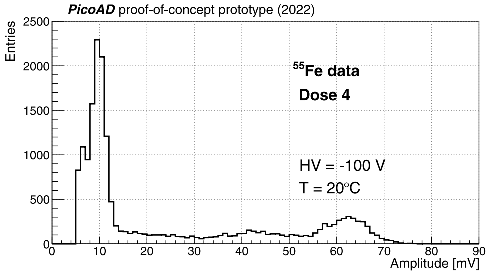

Fig. 2. Spectrum of the ^{55}Fe X-ray source obtained with one of the four analog pixels of the PicoAD proof-of-concept sensor with the highest dose of the gain layer implantation.

gain. The two possibilities correspond to generating a total charge of $(n_{tot})_{absorption} = G_e * n_i$ or $(n_{tot})_{drift} = G_h * n_i$. The electron gain G_e and the hole gain G_h are defined as the total charge divided by the primary charge, according to the carriers that initiated the avalanche mechanisms. The impact ionization coefficient of holes and electrons is expected to be different [3], hence the gain.

The induced current is amplified by the preamplifier with a gain G_{preamp}. The amplitude of the waveform seen by the oscilloscope is: $amp_e = G_{preamp} * G_e * n_i$; or $amp_h = G_{preamp} * G_h * n_i$.

Fig. 2 shows a typical spectrum obtained with the ^{55}Fe X-ray source. The spectrum has the double-peak structure that is expected from the PicoAD detector: the first peak (around 10 mV) is associated with the conversion in the drift region and the second (around 65 mV) is associated with the conversion in the absorption region. The entries between the two peaks are due to photons that convert in the inter-pixel area, where the gain is lower, or inside the gain layer.

The preamplifier has been calibrated using different methods that give compatible results: a Fe-55 source, a Cd-109 source and an infrared laser. The calibration have been found using a condition in which there is no charge multiplication. This condition is fulfilled if: the charge cluster is generated inside the drift region; the dose is the lowest, i.e. the dose 1; the High Voltage is the lowest possible to have the PicoAD detector fully depleted, i.e. 85 V. The condition of no charge multiplication is supported by the spectrum, which has only one peak in these conditions.

The calibration gives a preamplifier gain $G_{preamp} = 27$ mV/fC. With this factor, the amplitude of a signal can be converted in the equivalent charge. The gain for electron and holes is:

$$G_e = \frac{(n_{tot})_{absorption}}{n_i} = \frac{amp_e}{G_{preamp} * n_i}, \qquad (1)$$
$$G_h = \frac{(n_{tot})_{drift}}{n_i} = \frac{amp_h}{G_{preamp} * n_i}.$$

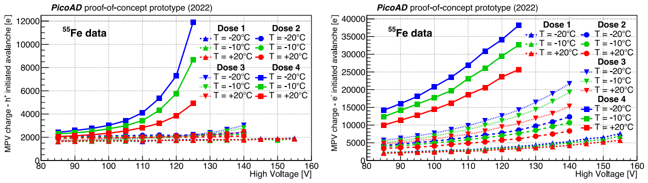

Fig. 3. MPV charge as a function of the High Voltage. Left: h^+ initiated avalanche. Right: e^- initiated avalanche.

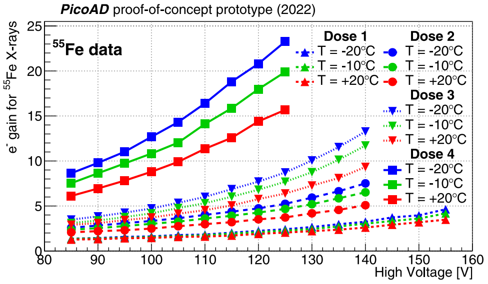

Fig. 4. Electron gain for ^{55}Fe X-ray as a function of the High Voltage.

3. Results

Spectra like the one in Fig. 2 have been acquired at different voltages and temperatures for each of the four doses of the gain layer implantation. The average amplitudes for hole and electron gain have been obtained as the most probable value of the local maxima associated with each peak of the spectrum. The calibration factor has been used to find the equivalent charge (see Fig. 3).

The values of the electron initiated avalanche gain have been obtained by dividing the total charge by the primary charge, as described by Eq. (1) in Section 2. The same procedure can be used to measure the hole initiated avalanche gain, thus making the structure of the PicoAD detector capable of allowing both the hole and the electron gain to be measured together. Fig. 4 shows the results of electron initiated avalanche gain for a ^{55}Fe X-ray source as a function of the High Voltage for one of the analog pixels.

The proof-of-concept prototypes are functional. Measurements with a ^{55}Fe X-ray source show different gains between the different levels of dopant concentration of the gain layer, with the gain increasing for higher doses. The gain increases for lower temperature, as expected [4].

4. Conclusions

Proof-of-concept prototypes of the monolithic PicoAD were produced at IHP using 5 μm (absorption) + 10 μm (drift) thick epitaxial layers. The highest electron gain measured with a ^{55}Fe X-ray source is 23. The hole gain can be measured in the same way as done for the electrons, making the PicoAD structure allow for measuring electron and hole gain at the same time.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The test and characterization of the prototypes was done in the context of the H2020 ERC Advanced Grant MONOLITH, grant ID: 884447, as well as of the Swiss National Science Foundation grant number 200020_188489.

References

[1] G. Iacobucci, L. Paolozzi, P. Valerio, Multi-junction pico-avalanche detector, European Patent EP3654376A1, US Patent US2021280734A1, 2018.

[2] G. Iacobucci, et al., Efficiency and time resolution of monolithic silicon pixel detectors in sige bicmos technology, J. Instrum. 17 (02) (2022) P02019.

[3] Y. Okuto, C.R. Crowell, Ionization coefficients in semiconductors: A nonlocalized property, Phys. Rev. B 10 (1974) 4284–4296.

[4] C.R. Crowell, S.M. Sze, Temperature dependence of avalanche multiplication in semiconductors, Appl. Phys. Lett. 9 (6) (1966) 242–244.